HESS Supporting Information for

Suspended sediment concentrations in Alpine rivers: from annual regimes to sub-daily extreme events

Amber van Hamel^{1,2,3}, Peter Molnar⁴, Joren Janzing^{1,2,3} and Manuela Irene Brunner^{1,2,3}

¹WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland ²Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland ³Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland ⁴Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland

| | | RMSE |] | R-squared | | | |
|-------------|--------|------------|----------------|-----------|------------|----------------|--|
| | Linear | Non-linear | Non-linear-Log | Linear | Non-linear | Non-linear-Log | |
| CH_2009 | 566.4 | 566.2 | 588.9 | 0.46 | 0.46 | 0.41 | |
| CH_2020 | 311.2 | 302.5 | 405.2 | 0.57 | 0.60 | 0.41 | |
| CH_{2056} | 172.6 | 169.3 | 233.5 | 0.51 | 0.52 | 0.46 | |
| CH_{2085} | 97.3 | 96.1 | 104.9 | 0.51 | 0.52 | 0.46 | |
| CH_2109 | 92.1 | 89.1 | 108.6 | 0.77 | 0.79 | 0.70 | |
| CH_2170 | 173.7 | 156.5 | 340.9 | 0.80 | 0.84 | 0.23 | |
| CH_2181 | 122.8 | 121.2 | 159.5 | 0.77 | 0.78 | 0.72 | |
| CH_2473 | 783.4 | 773.9 | 916.5 | 0.65 | 0.65 | 0.52 | |

Table S1. Root mean squared error (RMSE) and R-squared for the linear model, the nonlinear model, and the non-linear model with log-transformed data used to predict SSC based on turbidity data. The results are shown for each of the eight Swiss stations.

Table S2. The calibrated parameters a and b for the non-linear regression model for each of the eight Swiss stations.

| | a | b |
|---------|-------|-------|
| CH_2009 | 1.549 | 1.027 |
| CH_2020 | 9.067 | 0.767 |
| CH_2056 | 0.430 | 1.181 |
| CH_2085 | 0.779 | 1.201 |
| CH_2109 | 1.768 | 0.895 |
| CH_2170 | 3.411 | 0.842 |
| CH_2181 | 1.774 | 0.906 |
| CH_2473 | 4.098 | 0.881 |
| - | | |

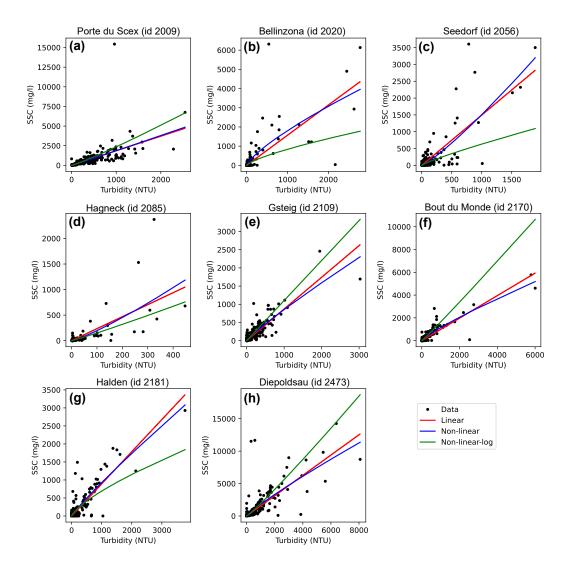


Figure S1. SSC bi-weekly samples plotted against the associated 10-minute turbidity measurements. The linear model (red), the non-linear model (blue), and the log-transformed nonlinear model (after back transformation) (green) are shown for each of the eight Swiss stations.

| Characteristics relat | ted to sediment transport | | |
|-----------------------|---|--------------------------------|--|
| Attribute | Description | Unit | Data source |
| slope_mean | Mean catchment slope | °C | QGIS and DEM / CamelsCH |
| Tmean_daily_mean | Mean daily air temperature | °C | CERRA |
| Tmean_daily_std | Standard deviation of mean daily air temperature | °C | CERRA |
| tp_daily_mean | Mean daily precipitation | mm d ⁻¹ | INCA and CPC |
| tp_daily_std | Standard deviation of mean daily precipitation | mm d ⁻¹ | INCA and CPC |
| tp_hourly_mean | Mean hourly precipitation | mm h ⁻¹ | INCA and CPC |
| tp_hourly_std | Standard deviation of mean hourly precipitation | mm h ⁻¹ | INCA and CPC |
| liqvsm_daily_mean | Mean daily liquid volumetric soil moisture | m ³ m ⁻³ | CERRA-Land |
| liqvsm_daily_std | Standard deviation of mean daily liquid volumetric soil moisture | m ³ m ⁻³ | CERRA-Land |
| icem_daily_std | Mean daily glacial melt | mm d ⁻¹ | PCR-GLOBWB 2.0 |
| icem_daily_std | Standard deviation of mean daily glacial melt | mm d ⁻¹ | PCR-GLOBWB 2.0 |
| snom_daily_mean | Mean daily snowmelt | mm d ⁻¹ | PCR-GLOBWB 2.0 |
| snom_daily_std | Standard deviation of mean daily snowmelt | mm d ⁻¹ | PCR-GLOBWB 2.0 |
| snocov_daily_mean | Mean daily snow cover | % | PCR-GLOBWB 2.0 |
| doy_swe_zero | Day of the year on which the snow water equivalent reaches zero (or a minimum) | - | PCR-GLOBWB 2.0 |
| p_frac_snow | Fraction of precipitation that falls as snow | - | LamaH-CE / CAMELS-CH |
| Qspecific_mean_d | Mean daily specific runoff | mm d ⁻¹ | Observations |
| high_q_freq | Frequency of high-flow days (≥ 9 times median daily flow) | d yr-1 | LamaH-CE / CAMELS-CH |
| high_prec_freq | Frequency of high-precipitation days (≥ 5 times mean daily precipitation) | d yr-1 | LamaH-CE / CAMELS-CH |
| runoff_ratio | Runoff ratio, computed as the ratio of mean daily runoff and mean daily precipitation | - | Calculated from Q observations and daily prepitation from INCA and CPC |
| stream_elas | Runoff-precipitation elasticity, i.e., the sensitivity of runoff to changes in precipitation at the annual timescale, using the mean daily runoff as reference | - | LamaH-CE / CAMELS-CH |

Figure S2. Selected static catchment characteristics that are related to sediment transport processes.

| Catchment charac | teristics related to sediment availability | | |
|------------------|---|---------------------|---|
| Attribute | Description | Unit | Data source |
| area | Catchment area | km² | LamaH-CE / CAMELS-CH |
| elev_mean | Mean catchment elevation | m.a.s.l. | LamaH-CE / CAMELS-CH |
| elev_ran | Range in catchment elevation (maximum - minimum elevation) | m | LamaH-CE / CAMELS-CH |
| urban_fra | Fraction of urban land (CLC classes 111, 112, 121, 122, 123, 124) | - | LamaH-CE / CAMELS-CH via CORINE |
| forest_fra | Fraction of forest land (CLC classes 311, 312, 313) | - | See above |
| glac_fra | Fraction of glaciers (CLC class 335) | - | See above |
| geo_low_ero_fra | Fraction of low erodible geology classes (incl. acid plutonic, intermediate plutonic, and basic plutonic rocks, metamorphites, carbonate sedimentary rocks, acid volcanic rocks) | - | LamaH-CE / CAMELS-CH via GLiM, geology classes clustered via method by Moosdorf et al. 2018 |
| geo_med_ero_fra | Fraction of median erodible geology classes (incl. siliciclastic sedimentary rocks, mixed sedimentary rocks, basic volcanic rocks, pyroclastics) | - | See above |
| geo_high_ero_fra | Fraction of high erodible geology classes (incl. unconsolidated sediments) | - | See above |
| sand_fra | Fraction of sand (of soil material < 2 mm) | - | LamaH-CE / CAMELS-CH via European Soil Database Derived data |
| Silt_clay_fra | Fraction of silt and clay (of soil material < 2 mm) | - | See above |
| grav_fra | Fraction of gravel (of overall soil) | - | See above |
| org_fra | Fraction of organic material (of overall soil) | - | See above |
| elon_ratio | Elongation ratio (Re) after Schumm (1956); ratio between the diameter D of a circle with an equivalent area as the area of the catchment, to the catchment length (Lc), Re = $1/Lc \times \sqrt{(4 \times A/\pi)} = D/Lc$ | - | LamaH-CE / QGIS and DEM |
| strm_dens | Stream density (DF); ratio of the total lengths of the streams (Lf) and the catchment area (A), DF = $\sum Lf / A$ | km km ⁻² | See above |
| meand_indx | Meandering index (Mi); ratio of the horizontal stream length (Ls) to the catchment length (Lc), Mi = Ls / Lc | km km-1 | See above |
| Upstr_lake_prec | Percentage of catchment area that is located upstream of big lakes (lake area > 1km²) | % | QGIS |
| Upstr_resv_perc | Percentage of catchment area located upstream of reservoirs | % | QGIS |

| Figure | S 3. | Selected static catchment characteristics that are related to sediment availability. |
|--------|-------------|--|
|--------|-------------|--|

| Time-varying characteristics | | | | | | | |
|--|--------------------------------|--|--|--|--|--|--|
| Description | Unit | Data source | | | | | |
| Hourly precipitation | mm d ⁻¹ | INCA and CPC | | | | | |
| Daily glacial melt | mm d ⁻¹ | PCR-GLOBWB 2.0 | | | | | |
| Daily snowmelt | mm d ⁻¹ | PCR-GLOBWB 2.0 | | | | | |
| Daily specific runoff | mm d ⁻¹ | Observations | | | | | |
| Daily liquid volumetric soil moisture | m ³ m ⁻³ | CERRA-Land | | | | | |
| Daily snow cover; percentage of catchment area that is snow- covered (with snow water equivalent > 0.1mm) | % | PCR-GLOBWB 2.0 | | | | | |
| Daily proxy for sediment availability; ratio between the annual cumulative sSSY and the long-term cumulative sSSY regime to see if more/less sediment than usual has been mobilized in the catchment during earlier events. | - | Calculated from SSC and discharge observations | | | | | |

Figure S4. Selected time-varying hydro-climatic and catchment-related characteristics.

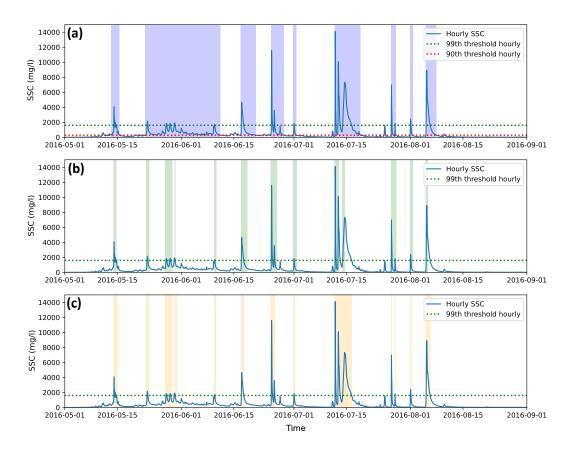


Figure S5. Comparison of three different methods to define the end of extreme SSC events. The peak value of all events exceeds a locally defined 99th percentile threshold and the start of the event is based on a rapid increase in the slope of SSC prior to the SSC peak. The end of the event is defined as (a) the first time step after peak SSC on which the SSC is below the 90th percentile threshold, (b) the first time step when the slope is less than Δ -10 mg l⁻¹ h⁻¹, and (c) the first time step when the SSC is below 0.4 * *peak_SSC* or the 99th threshold (lowest value is selected).

Table S3. Number of extreme SSC events and the percentage of the total number of events per event type. The results are shown for three methods that have a different definition for the start- and end of the events. Method 1: start/end when the SSC is above/below a fixed 90th percentile threshold. Method 2: start and end when the slope is more than $\Delta + 20 / \Delta - 10$ SSC/hour. Method 3: Start when the slope exceeds $\Delta + 20$ and the end when the SSC is below $0.4 * peak_SSC$ or the 99th threshold (lowest value is selected).

| | Num | ber of events | s (-) | Percentage of total number (%) | | | | |
|--------------|----------|---------------|----------|--------------------------------|----------|----------|--|--|
| | Method 1 | Method 2 | Method 3 | Method 1 | Method 2 | Method 3 | | |
| Total events | 2020 | 2423 | 2398 | 100.0 | 100.0 | 100.0 | | |
| RainH | 1353 | 1540 | 1547 | 67.0 | 63.6 | 64.5 | | |
| RainL | 400 | 504 | 494 | 19.8 | 20.8 | 20.6 | | |
| Snow | 79 | 124 | 110 | 3.9 | 5.1 | 4.6 | | |
| RainL & Snow | 70 | 86 | 82 | 3.5 | 3.5 | 3.4 | | |
| RainH & Snow | 50 | 57 | 56 | 2.5 | 2.4 | 2.3 | | |
| Ice | 35 | 54 | 54 | 1.7 | 2.2 | 2.3 | | |
| RainL & Ice | 15 | 25 | 23 | 0.7 | 1.0 | 1.0 | | |
| RainH & Ice | 12 | 20 | 22 | 0.6 | 0.8 | 0.9 | | |
| Snow & Ice | 6 | 13 | 10 | 0.3 | 0.5 | 0.4 | | |

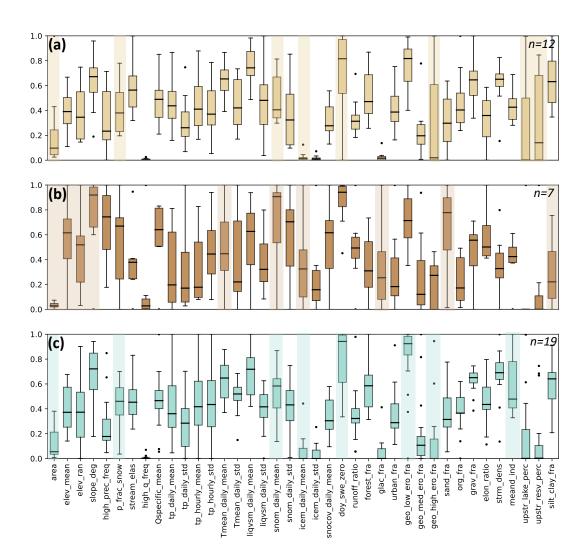


Figure S6. (a) Distribution of all static catchment characteristics for the catchments that belong to (a) Cluster 1, (b) Cluster 2, and (c) Cluster 3. To be able to compare the results within and among clusters, all catchment-related and hydro-meteorological attributes were normalized to the range 0-1 (z-score).

| median_SSC | | | Peak1_doy Peak_magdiff_rel | | | Peak_numb Peak_timediff_do | | | _doy | |
|---------------------|--------|---------------------|----------------------------|---------------------|---------|----------------------------|---------|---------------------|---------|--------|
| median_SSC - | 1 | Peak1_doy - | 1 | Peak_magdiff_rel - | 1 | Peak_numb - | 1 | Peak_timediff_doy - | 1 | |
| snom_daily_mean - | 0.68 | geo_low_ero_fra - | 0.44 | tp_daily_std - | 0.45 | stream_elas - | 0.4 | upstr_resv_perc - | 0.36 | |
| snocov_daily_mean - | 0.67 | sand_fra - | 0.44 | tp_hourly_std - | 0.43 | strm_dens - | 0.35 | Peak_numb - | 0.29 | |
| elev_mean - | 0.64 | elev_mean - | 0.42 | stream_elas - | 0.38 | urban_fra - | 0.35 | liqvsm_daily_std - | 0.28 | |
| runoff_ratio - | 0.6 | p_frac_snow - | 0.42 | liqvsm_daily_std - | 0.35 | silt_clay_fra - | 0.32 | geo_high_ero_fra - | 0.27 | |
| sand_fra - | 0.58 | icem_daily_std - | 0.39 | snom_daily_std - | 0.33 | Peak_timediff_doy - | 0.29 | Qspecific_mean - | 0.24 | |
| snom_daily_std - | 0.58 | icem_daily_mean - | 0.38 | slope_deg - | 0.26 | tp_hourly_mean - | 0.26 | geo_med_ero_fra - | 0.21 | |
| p_frac_snow - | 0.57 | snocov_daily_mean - | 0.37 | doy_swe_zero - | 0.25 | liqvsm_daily_mean - | 0.25 | stream_elas - | 0.18 | |
| glac_fra - | 0.55 | glac_fra - | 0.36 | Qspecific_mean - | 0.25 | forest_fra - | 0.25 | urban_fra - | 0.17 | |
| icem_daily_std - | 0.51 | snom_daily_mean - | 0.33 | tp_daily_mean - | 0.25 | Tmean_daily_mean - | 0.24 | snocov_daily_mean - | 0.16 | |
| icem_daily_mean - | 0.5 | slope_deg - | 0.31 | grav_fra - | 0.23 | grav_fra - | 0.24 | runoff_ratio - | 0.16 | |
| slope_deg - | 0.42 | snom_daily_std - | 0.27 | tp_hourly_mean - | 0.21 | tp_daily_mean - | 0.23 | snom_daily_mean - | 0.15 | |
| geo_high_ero_fra - | 0.37 | runoff_ratio - | 0.26 | snom_daily_mean - | 0.2 | tp_daily_std - | 0.21 | median_SSC - | 0.15 | |
| Qspecific_mean - | 0.36 | median_SSC - | 0.21 | strm_dens - | 0.17 | area - | 0.2 | high_q_freq - | 0.15 | |
| doy_swe_zero - | 0.32 | elev_ran - | 0.18 | median_SSC - | 0.16 | upstr_lake_perc - | 0.19 | high_prec_freq - | 0.13 | |
| elev_ran - | 0.31 | elon_ratio - | 0.16 | geo_low_ero_fra - | 0.14 | Tmean_daily_std - | 0.15 | glac_fra - | 0.12 | |
| Peak1_doy - | 0.21 | meand_ind - | 0.025 | high_prec_freq - | 0.13 | liqvsm_daily_std - | 0.11 | elev_ran - | 0.12 | |
| Peak_magdiff_rel - | 0.16 | Qspecific_mean - | 0.0092 | snocov_daily_mean - | 0.12 | tp_hourly_std - | 0.094 | org_fra - | 0.12 | 1.00 |
| Peak_timediff_doy - | 0.15 | upstr_lake_perc - | -0.0041 | high_q_freq - | 0.096 | org_fra - | 0.091 | snom_daily_std - | 0.12 | - 0.75 |
| high_prec_freq - | 0.14 | Tmean_daily_std - | -0.015 | runoff_ratio - | 0.096 | geo_high_ero_fra - | 0.079 | tp_daily_mean - | 0.11 | - 0.50 |
| geo_low_ero_fra - | 0.12 | tp_hourly_std - | -0.018 | p_frac_snow - | 0.09 | geo_med_ero_fra - | 0.075 | area - | 0.11 | - 0.25 |
| liqvsm_daily_std - | 0.088 | doy_swe_zero - | -0.023 | Peak_timediff_doy - | 0.069 | upstr_resv_perc - | 0.044 | icem_daily_mean - | 0.089 | - 0.00 |
| upstr_resv_perc - | 0.068 | tp_hourly_mean - | -0.048 | elev_mean - | 0.068 | meand_ind - | 0.021 | elev_mean - | 0.084 | |
| elon_ratio - | 0.028 | org_fra - | -0.095 | elon_ratio - | 0.055 | geo_low_ero_fra - | 6.5e-05 | icem_daily_std - | 0.083 | 0.25 |
| high_q_freq - | -0.039 | liqvsm_daily_std - | -0.1 | silt_clay_fra - | 0.038 | Peak_magdiff_rel - | -0.091 | upstr_lake_perc - | 0.073 | 0.50 |
| grav_fra - | -0.13 | tp_daily_std - | -0.11 | forest_fra - | 0.023 | elev_ran - | -0.13 | Peak_magdiff_rel - | 0.069 | 0.75 |
| urban_fra - | -0.14 | area - | -0.11 | sand_fra - | -0.0089 | high_q_freq - | -0.2 | grav_fra - | 0.061 | -1.00 |
| area - | -0.18 | Peak_magdiff_rel - | -0.11 | geo_high_ero_fra - | -0.049 | high_prec_freq - | -0.21 | tp_daily_std - | 0.059 | |
| tp_daily_mean - | -0.24 | geo_high_ero_fra - | -0.11 | Tmean_daily_mean - | -0.056 | Peak1_doy - | -0.23 | p_frac_snow - | 0.05 | |
| org_fra - | -0.26 | high_prec_freq - | -0.13 | liqvsm_daily_mean - | -0.06 | doy_swe_zero - | -0.24 | liqvsm_daily_mean - | 0.032 | |
| Peak_numb - | -0.27 | tp_daily_mean - | -0.15 | Peak_numb - | -0.091 | elon_ratio - | -0.26 | slope_deg - | 0.019 | |
| geo_med_ero_fra - | -0.27 | grav_fra - | -0.17 | urban_fra - | -0.092 | Qspecific_mean - | -0.27 | silt_clay_fra - | 0.011 | |
| tp_daily_std - | -0.28 | strm_dens - | -0.18 | Peak1_doy - | -0.11 | p_frac_snow - | -0.27 | tp_hourly_mean - | -0.0073 | |
| tp_hourly_std - | -0.29 | high_q_freq - | -0.21 | geo_med_ero_fra - | -0.12 | median_SSC - | -0.27 | sand_fra - | -0.0087 | |
| upstr_lake_perc - | -0.3 | Peak_numb - | -0.23 | Tmean_daily_std - | -0.12 | snom_daily_std - | -0.27 | Tmean_daily_mean - | -0.073 | |
| stream_elas - | -0.3 | upstr_resv_perc - | -0.28 | upstr_lake_perc - | -0.15 | elev_mean - | -0.29 | strm_dens - | -0.081 | |
| tp_hourly_mean - | -0.33 | forest_fra - | -0.33 | upstr_resv_perc - | -0.15 | sand_fra - | -0.29 | doy_swe_zero - | -0.14 | |
| strm_dens - | -0.39 | urban_fra - | -0.38 | org_fra - | -0.18 | icem_daily_mean - | -0.33 | Tmean_daily_std - | -0.14 | |
| Tmean_daily_std - | -0.4 | stream_elas - | -0.4 | glac_fra - | -0.25 | snocov_daily_mean - | -0.33 | forest_fra - | -0.15 | |
| meand_ind - | -0.49 | Tmean_daily_mean - | -0.43 | icem_daily_mean - | -0.26 | slope_deg - | -0.33 | tp_hourly_std - | -0.15 | |
| Tmean_daily_mean - | -0.58 | silt_clay_fra - | -0.44 | icem_daily_std - | -0.27 | icem_daily_std - | -0.34 | geo_low_ero_fra - | -0.26 | |
| silt_clay_fra - | -0.58 | geo_med_ero_fra - | -0.47 | meand_ind - | -0.3 | snom_daily_mean - | -0.36 | elon_ratio - | | |
| liqvsm_daily_mean - | -0.58 | liqvsm_daily_mean - | -0.5 | elev_ran - | -0.37 | glac_fra - | -0.36 | meand_ind - | | |
| forest_fra - | -0.64 | Peak_timediff_doy - | -0.83 | area - | -0.46 | runoff_ratio - | -0.43 | Peak1_doy - | -0.83 | |

Figure S7. Pearson correlations of the static characteristics with the five MST-indicators that have been used for the clustering of the annual SSC cycles. The black boxes highlight the static characteristics that show a moderate correlation (correlation coefficient >0.5) with the magnitude of the SSC regime (*median_SSC*).

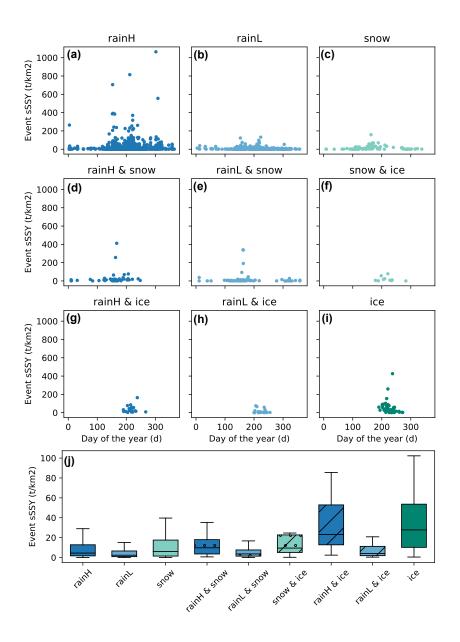


Figure S8. Area-specific suspended sediment yield (sSSY) is grouped by event type. Panels (a-i) illustrate the variation of sSSY over time with the outliers. Panel(j) illustrates the distribution of sSSY for each even type (without outliers), with the median value represented by a horizontal black line.

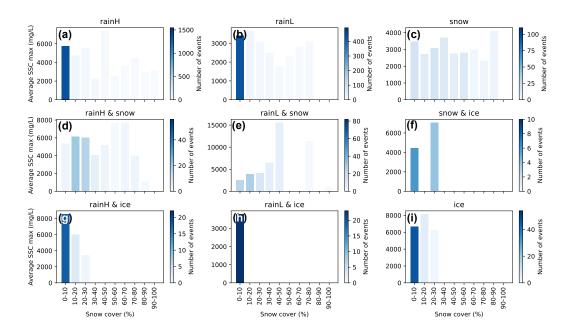


Figure S9. Snow cover prior to extreme SSC events can vary from 0-100%. Per event type and for each of the 10 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark blue means that most events of that event type belong to that interval.

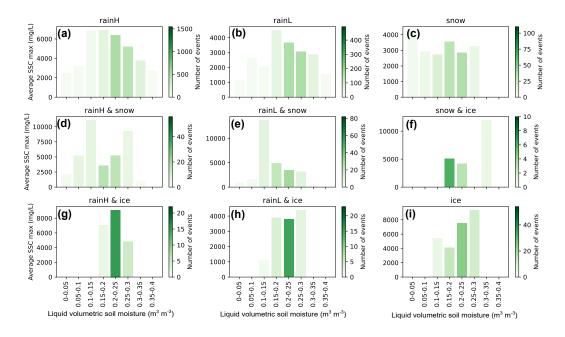


Figure S10. Liquid volumetric soil moisture generally varies from 0-0.4 m^3/m^3 . Per event type and for each of the 8 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark green means that most events of that event type belong to that interval.

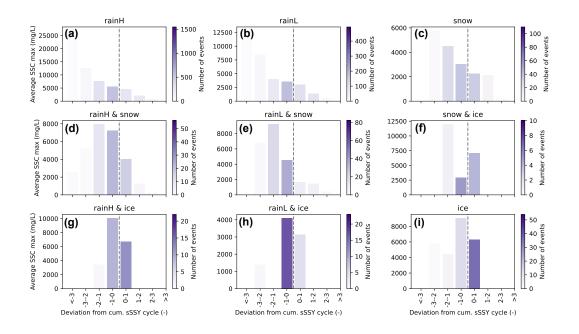


Figure S11. Prior to the extreme SSC event, the deviation of the daily cumulative sSSY from the annual mean cumulative sSSY cycle can be positive or negative. Positive values indicate that prior to the event, more sediment has been transported by the river than usual. Negative values indicate that less sediment than usual has been transported. Per event type and for each of the 8 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark purple means that most events of that event type belong to that interval.